# PEER REVIEW

## PROPOSED DIESEL SULFUR REGULATIONS AND EMISSION BENEFITS OF CURRENT REGULATIONS

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# INTRODUCTION

The California Air Resources Board (ARB) requested an independent peer review of (1) the proposed revisions to the California Diesel Fuel regulations, including a standard for lubricity, and (2) benefits quantified for the existing regulations.

Reviewers were provided with a copy of the staff report[1] for the proposed revisions to regulations. The report includes, as Appendix D, a staff review of the benefits of the existing regulations. Reviewers were also provided with copies of previous staff reports and a CD containing references cited in the staff report.

The regulation for reduced sulfur content of diesel fuel is consistent with regulations promulgated earlier by the U. S. Environmental Protection Agency (EPA) for sulfur content of diesel fuel intended for on-highway vehicles.[2] The EPA recently published a notice of proposed rulemaking for reduction of the sulfur content of offroad diesel fuel.[3]

In addition, EPA has recently reviewed studies regarding the effects of diesel fuel properties on emissions. This reviewed was initiated in response to EPA's concern about NOx emission reduction credits claimed by Texas for a state implementation plan (SIP) measure requiring low-emission diesel (LED) fuel similar to California diesel. In addressing this issue, EPA commissioned a contractor report by Southwest Research Institute (SwRI),[4] and prepared a staff discussion document.[5] EPA ultimately provided an estimate of the benefits of the Texas program, but declined to publish a general model for the effect of diesel fuel properties on emissions. Instead, EPA published a simpler correlation that dealt with the effects of cetane additives on NOx emissions.[6]

Thus, the issues addressed in this review can draw not only upon the technical literature but also upon previous analyses of such literature related to the regulatory issues considered in the staff report under review here.

The review is organized into two sections that address the two issues posed here: the proposed regulation amendments and the effect of the current regulations.

# PROPOSED REVISIONS TO THE REGULATIONS

The proposed revisions modify existing regulations for diesel fuel sold in California. The current regulations require a maximum sulfur concentration of 500 parts per million by weight (ppmw) and a maximum aromatics content of 10 percent by volume (10%v). Refiners may produce alternative diesel fuels to comply with the 10%v aromatics limit if they show, by engine testing, that the alternative fuel provides the same emission benefits. Although low-sulfur diesel fuels are known to have reduced lubricity, compared to diesel fuels with higher sulfur, the current regulations do not have a lubricity standard. However, California refiners have voluntarily agreed to place additives in the fuel to provide adequate lubricity. Diesel fuel meeting the current regulations must be used in all motor vehicles.*

The main regulatory change proposed here is a reduction of the maximum sulfur content of diesel fuel from 500 ppmw to 15 ppmw. This limitation would be phased in starting on June 1, 2006. In addition to the sulfur limit, the proposed rule revisions would make the following changes.

- Set a lubricity standard to alleviate any effects of reduced lubricating properties of fuels with the reduced sulfur content.
- Change the allowable limit for sulfur in fuels that are used to certify new diesel engines.
- Provide a set of fuel specifications that refiners could use as an alternative to 10%v aromatics limit without doing actual engine tests.
- Make various changes in the procedures that refiners use to certify an alternative fuel that satisfies the 10%v aromatics requirement.
- Adopt an airborne toxic control measure (ATCM) requiring that that this fuel be used in nonvehicular engines, except those used in locomotives and marine vessels.
- Make various changes in definitions and test methods and exempt the military from use of this diesel fuel.

These individual elements of the rule are discussed below.

## Reduced sulfur content

The major purpose for the rule revisions is based on the need for very low sulfur fuel to allow future emission control technologies – such as catalytic particulate filters and NOx adsorbers – for diesel engines. ARB and EPA expect these technologies to be used for

* The ARB regulations apply to all diesel-fueled motor vehicles as defined in section 415 of the state vehicle code; these are self-propelled devices "by which any person or property may be propelled, moved, or drawn upon a highway, excepting a device moved exclusively by human power or used exclusively upon stationary rails or tracks."

diesel emission standards in 2007 and later; these engine emission standards are already required by ARB (and EPA) rules.

In addition to the use of these technologies for new engines, ARB also seeks the use of the catalytic particulate filters for retrofit applications as part of its plan for reducing the risk from exposure to diesel particulate matter from existing engines. This need for low-sulfur fuel in advanced engine emission control technologies has been noted for several years now and EPA promulgated a rule for low sulfur fuel at the same time as it promulgated a rule for the new engine standards for 2007. The explanation for this need is appropriately expressed in the staff report and is consistent with references cited in the staff report and other sources.

The proposed 15 ppmw sulfur limit will also provide a proportionate reduction in gaseous $SO_2$ emissions from diesel engines and a reduction in the sulfate formation in diesel exhaust.

### Technology for producing 15 ppmw sulfur diesel fuel

The removal of sulfur from liquid and gaseous fuels has been long regarded as the most effective way to remove sulfur compounds from the exhaust of systems that burn such fuels. Technology for such sulfur removal processes also has a long history. It was initially developed to reduce sulfur content of refinery process streams to protect catalysts used in the refining process whose activity was reduced by sulfur. The basic process involves the addition of hydrogen to the fuel stream over a catalyst. The hydrogen reacts with the sulfur to form hydrogen sulfide, $H_2S$, which is then removed and treated to produce elemental sulfur. This basic process is known as hydrotreating, and variations of this process are in use or proposed for advanced use.

The application of sulfur removal to diesel fuel on a widespread basis is a more recent application of this technology. The current level of 500 ppmw was required in the South Coast Air Basin and Ventura County starting in 1985 and was required by California and federal regulations in 1993. Before these dates, the sulfur content of diesel fuel was limited by the specifications of the American Society for Testing and Materials (ASTM) to a level of 5000 ppmw, but was generally less than this level for highway diesel fuel. The production of diesel fuel with the low levels of sulfur required by the regulations proposed here (and similar EPA regulations) extends this technology beyond the current capacity of most refineries. The ARB staff report notes that some new technologies may be used to meet the 15 ppmw level, but this level can be met with existing technology.[*]

Additional background on the technology for producing 15 ppmw sulfur diesel fuel can be found in EPA regulatory documents. In the regulatory impact analysis for the EPA rule, the Agency noted the variability among refineries in the U.S. and the need to provide flexibility for individual refineries.[7] Several comments to EPA's 15 ppmw sulfur

[*] The staff report notes that about 20% of the diesel fuel currently produced in California meets the 15 ppmw sulfur level.

requirement proposal noted that the lead time provided might not be sufficient for the development of alternative, lower-cost technologies to the expansion of conventional hydrotreating.[8] Recent reviews by EPA[9] and a subcommittee of the Clean Air Act Advisory Committee[10] generally concluded that, for the national rule, the refining industry is making appropriate progress to produce 15 ppmw sulfur diesel fuel for highway engines in 2006. The review subcommittee report noted that some of its members raised issues about the ability of the refining industry to meet the national demand. EPA is planning one or more workshops to discuss various issues related to the fuel and engine standards for highway diesel.[*]

The situation for California refineries will be different from the national picture. California refineries have the 10%v aromatics limitation, which is not applicable nationally, and the current sulfur levels for California diesel fuel are less than the national average. The ARB staff report contains, in Appendix L, copies of two surveys that were sent to all California refineries that produce diesel fuel. No particular problems or concerns about achieving the 15 ppmw sulfur level are cited in the staff report. Although there are always questions about meeting future standards, some technologies for meeting the 15 ppmw sulfur level are well established and uncertainties in the application of these technologies are much less than the uncertainties about the vehicle emission control technologies required in the same time frame.

The production capacity and demand level for diesel fuel produced in California, taken from pages 86 and 87 of the ARB staff report, are shown in Table 1.

**Table 1 – California Diesel Fuel Production and Capacity in 2007 (thousands of barrels per day)**

| Fuel Type | Projected Production | Production Capacity |
|---|---|---|
| California Diesel | 231 | 275 |
| Federal Diesel | 132 | 120 |
| **Total** | **363** | **395** |

This table shows that the expected total capacity is only 9% greater than the expected total production (which presumably is the demand). For California diesel, the capacity is 19% greater than the expected production. The production is described on page 86 as the production of on-road diesel. However, on page 110 the derivation of the 2007 production figure, 231 thousand bpd, is stated to be on-road and off-road diesel. As noted on page 110, the 2007 production data assume an increase of about 4% per year. If this rate of increase continues, the production would have to exceed the 2007 capacity by 2012.

[*] A workshop is currently scheduled for August 6-7, 2003 in Chicago. Information is available on the web site: http://www.epa.gov/otaq/diesel.htm#engine-workshops.

The report seems to indicate that there will be no problem with producing the required quantities of California diesel fuel; however two concerns come to mind: (1) this balance will only last a few years without additional refining capacity, and (2) the contradiction between the use of "on-road" on pages 86-87 and the description of "on-road and off-road" on page 110 should be clarified and expanded to include the production of diesel fuel for use in stationary and portable engines.

### Cost of producing 15 ppmw sulfur diesel fuel

The technology required to produce diesel fuel meeting the low sulfur requirement, and the cost of meeting this requirement, will vary among individual refiners in the state. The costs of the proposed regulations are discussed in Chapter XVIII. The overall cost is estimated at 2 to 5 cents per gallon during the first year of production in which "temporary limitations on supply and production … could result in potential first year costs of up to 1 cent per gallon." In subsequent years, the cost estimate is between 2 and 4 cents per gallon. The largest component of this cost is the production cost, discussed below. The remaining components are distribution system costs, fuel economy penalty, and lubricity additives whose combined costs are estimated to range from 0.2 to 1.1 cents per gallon.

The average statewide cost of 2.2 to 2.7 cents per gallon to produce the 15 ppmw sulfur fuel is discussed on pages 110 and 111. This cost is based on the capital costs reported in the refiner surveys, which showed a total statewide capital cost between $170 million and $250 million. To arrive at a cost per gallon, the ARB staff has assumed that this capital cost will be amortized over a ten-year period at a rate of 7% per year. This produces a capital recovery factor of 0.1424. Differences in the rate and period assumptions made to compute this factor often lead to the most significant discrepancies in different cost estimates. For example, a decision to amortize the cost over a five-year period at a rate of 10% would produce a capital recovery factor of 0.2638; this would increase the annualized capital cost by 85%.

The statewide operating and maintenance costs from the proposed revisions are estimated to range from $50 million to $60 million per year. (This estimate is not consistent with a previous statement in the report that the annual O&M costs range from 10% to 20% of the initial capital expenditure; this percentage range would give annual O&M cost estimates of $17 million to $50 million.) The total annual cost, the sum of the annual O&M cost and the annualized capital cost, is divided by the 2007 production estimate of 3.5 billion gallons to give the cost range of 2.2 to 2.5 cents per gallon. Cost estimates for individual refineries range from zero to 11 cents per gallon.

Other cost estimates for production of 15 ppmw sulfur fuel are shown in Table XVIII-4 on page 115 of the staff report. Cost estimates prepared by the South Coast Air Quality Management District (as adjusted by ARB staff for consistency with their calculations) range from 1.3 to 3.5 cents per gallon. All other studies examined, which were based on the national rule that starts from a higher sulfur baseline, ranged from 4.2 to 6.8 cents per gallon. The February 2002 study by MathPro, which shows a cost of 5 to 8 cents per gallon, was based on refineries in one Petroleum Administration District for

Defense, PADD 4, which is expected to have the highest compliance costs for the national rule.

Cost estimations typically vary over a wide range and the differences between the cost estimates in the staff report and those in the other references cited are within the range of variability usually encountered for such estimates. The lower estimates for control costs in California, as compared to national data, are expected because California refineries are already producing lower sulfur diesel fuel. In summary, the cost estimates are reasonable ones, given the uncertainty in such estimates and the differences between California refineries and national refineries for which most of the other cost estimate data are prepared.

## Lubricity requirement

The discussion of this topic in the staff report presents a good picture of the following elements for this proposed regulation:

- the requirements for lubricating properties of diesel fuel
- the need for a simple test that provides a measure of fuel lubricity
- the current bench-scale lubricity tests known as SLBOCLE (scuffing load ball-on-cylinder lubricity evaluator) and HFRR (high frequency reciprocating rig)
- the problems of finding an exact correlation among these two bench-scale tests and the more extensive (and expensive) wear tests
- the current voluntary standard in California for SLBOCLE level of 3,000 grams or higher
- the need for additional studies in this area and the plans of the Coordinating Research Council (CRC) for such studies
- the current ASTM ballot for an HFRR maximum wear standard of 520 µm.

The proposed requirement for a lubricity standard in the ARB regulations is different from the current approach in California that relies on refiners maintaining appropriate lubricity levels. It also differs from the approach proposed by EPA in its regulation for 15-ppmw sulfur highway diesel fuel. EPA recognized the need for diesel fuel lubricity during their rulemaking for low-sulfur, highway diesel fuel; however EPA decided not to set a standard. Instead, the Agency relied on refiners voluntarily producing fuels with appropriate lubricating properties to meet the needs of their customers.

The issue of setting a lubricity standard is more a policy issue than a technical issue. The staff proposal specifies the HFRR test with a maximum wear standard of 520 µm. This is the same as the one currently under consideration by the ASTM. Furthermore, the staff proposes two additional elements of the standard. The first is a reevaluation of data from subsequent studies to modify the standard for the 15 ppmw diesel fuel if required. The second element is to withdraw the standard if the ASTM adopts a lubricity standard. Such a standard for diesel fuel would be enforced in California by the

Department of Weights and Measures. This seems like a reasonable approach to including the lubricity standard in the emission regulations. The decision to include such a standard or to rely on a voluntary approach does not change the technical rationale; lower sulfur diesel fuels will have lower lubricity that will accelerate wear in diesel engine components that rely on the lubricating property of the fuel.

## Other changes

A variety of other changes are proposed in the regulations. Some of these are administrative changes; others have technical implications. These proposed changes are discussed below.

### Establishment of an alternative formulation that satisfies the 10%v aromatics standard

This an extension of the existing provision that allows refiners to produce alternative fuel formulations, which achieve the same emissions reduction as a fuel that meets the 10%v aromatics standard. At present, the only way to qualify an alternative fuel formulation is to show by engine testing that the fuel has equivalent emission reductions. Under this proposed change, any fuel that has required levels of total aromatics, polycyclic aromatics, density, cetane number, nitrogen content and sulfur content shown in Table XI-3 on page 63 would be an acceptable diesel fuel. The various levels for these properties were determined by examining data on existing diesel fuels. This proposed change is a logical extension of the provisions for alternative diesel blends. The current provision requiring testing and the proposed new provision for an alternative fuel formulation recognize that properties of diesel fuels have significant interrelationships. Different fuel formulations, with different sets of properties, may achieve the same emission results.

The properties included in the proposed equivalency levels include those typically used to evaluate the effect of diesel fuels on emissions; in particular, the density (API gravity), total and polycyclic aromatic content and cetane number are commonly used to evaluate the impact of different fuel formulations on emissions. Since the proposed equivalency levels correspond to average properties for California diesel fuels, a fuel meeting all these levels should have equivalent emissions benefits. However, there is no demonstration that this will be the case. It is also interesting to note that only one of the five fuels shown in Table XI-1 would meet the equivalency limits. (This is a fuel that meets the requirements specified by executive order G-714-001; all others have a polycyclic aromatic content that is larger than the one specified in the proposed new equivalent limits.)

### Modification of the criterion for accepting an alternative fuel formulation

The tests for alternative fuel formulations compare emissions from a reference fuel that meets the 10%v aromatics limitation and a proposed alternative fuel, known as the candidate fuel. The criterion for accepting the candidate fuel is that the mean emissions for the candidate and reference fuel, $\overline{x}_C$ and $\overline{x}_R$, respectively, satisfy the following inequality.

$$\bar{x}_C \le \bar{x}_R + \delta - t_{0.15,2n-2}\ S_P \sqrt{\frac{2}{n}} = \bar{x}_R(1+\varepsilon) - t_{0.15,2n-2}\ S_P \sqrt{\frac{2}{n}}$$

Here n is the number of tests for each fuel, $S_P$ is the pooled standard deviation for the tests on the two fuels, and $t_{0.15,2n-2}$ is the 15% percentage point of the t distribution for 2n - 2 degrees of freedom. At least 40 tests – 20 on each fuel – are required. The (1 + ε) term is designed to provide a margin of safety to the company proposing the candidate fuel. In the present regulation ε = 2% for NOx, 4% for particulate matter (PM) and 12% for the soluble organic fraction (SOF) of particulate matter. The proposed regulations would cut these ε values in half (1% for NOx, 2% for PM and 6% for SOF). This would reduce the cushion for qualifying the alternative fuel.

The proposed revisions to the allowed values of ε are based on an analysis of data reported for 335 tests conducted in the same laboratory on the fuels of 16 large refiners. The analysis evaluated the minimum values of ε that would be required to qualify the average fuel; these were 0.45% for NOx, 1.2% for PM and 5.2% for SOF. The proposed maximum value of ε is 0.55 percentage points greater than this minimum for NOx and 0.80 percentage points greater than the minimum for PM and SOF. (Expressed as a ratio, the proposed ε values are 2.2, 1.7, and 1.2 times the minimum values for NOx, PM and SOF, respectively.) There is no analysis of how the proposed ε values were determined from the calculations. It would be interesting to show how many of the fuels that qualified with the previous ε values would not qualify with the new ones.

Reducing the allowed value of ε should reduce the possibility that alternative formulations with higher emissions would be approved. The approach of setting an allowed value of ε that is different for each species and related to the measurement error for each species is an appropriate approach. However, the quantitative effects of the proposed changes on emissions or on the likelihood of accepting a candidate fuel are not clear.

### Airborne toxics control measure

The report recommends that the Board adopt an airborne toxics control measure (ATCM) that would require California diesel fuel to be burned in nonvehicular engines. Such a measure would require local air pollution control districts to place this requirement in their local rules. The combustion process in stationary and portable engines may differ from that in onroad and offroad engines, but the combustion process is similar enough to provide benefits from this fuel. Local districts often require the use of such fuel in stationary engines at present, at least in the specification of best available control technology for new engines. According to the staff report, most stationary diesel engines now use California diesel fuel because of the single fuel distribution network. The effect of this proposed ATCM is to ensure that this continues in the future when local districts pass regulations requiring the use of retrofit equipment on stationary diesel engines.

**Other changes not reviewed in detail**

This section lists additional changes that are proposed and provides brief comments on those changes.

- The level of sulfur allowed in fuel, which is used to certify new engines to their emission standards, is adjusted to be consistent with the 15 ppmw sulfur requirement. This follows a longstanding practice of using certification fuels that match fuels used in the marketplace.
- Similarly, the level of sulfur in candidate and reference fuels, for alternative fuel formulations, is adjusted to be consistent with the new 15 ppmw sulfur limit.
- The sulfate credit, which was applied to alternative fuel formulations with sulfur levels less than 500 ppmw required by the current regulations is eliminated. With the new 15 ppmw sulfur level, this credit will be negligible and need not be considered.
- Additional property data on alternative fuel formulations is required to be reported. Since the emissions values of diesel fuels can depend on a range of interrelated properties, this change seems reasonable.
- Expand the reporting requirements for candidate fuels to include all the properties that must be reported for reference fuels, and require candidate fuels to have properties within certain ranges. This change is aimed at ensuring that all relevant properties of equivalent fuels are maintained in a range that produces low emissions. This change seems reasonable; however, there is no discussion of any problems that it may cause in actual production of the alternative fuel formulations.
- Eliminate the use of number one diesel fuel as a candidate fuel to allow production of number two diesel fuel. The staff's reasoning that number one diesel has better emissions performance is correct. However, this change may be redundant to the proposed changes in the property specifications for the candidate and reference fuels.
- The proposed change in the test method for sulfur to allow accurate measurements of lower sulfur levels is appropriate.
- The revision of definitions, miscellaneous wording changes, and the exemption for military operations do not appear to be technical issues and were not reviewed.

## Environmental effects

Chapter XVII reviews the potential environmental effects of the proposal. The basic intent of the proposed revisions is to enable the use of advanced emission control systems on diesel engines, which would provide additional reductions in NOx and PM emissions from those engines. In addition, some reductions in sulfur oxides would result from these revisions. Thus, the main effect of implementing the proposal is an environmental benefit. The environmental chapter examines possible side effects that would cause an environmental disbenefit.

The effect on water quality is analyzed by considering changes in the solubility that are likely to occur because of the production of lower sulfur diesel fuel. The report notes that such changes are expected to reduce the solubility of diesel fuel components in water and consequently there should be no deleterious impact on water quality. No water-quality effects have been noted since the change from high-sulfur fuels to the current statewide average level of 133 ppmw.

The report concludes that the proposed revisions "could have a small net effect on global warming." Although the report considers emissions of methane ($CH_4$) and nitrous oxide ($N_2O$), most of the analysis is directed to changes in carbon dioxide ($CO_2$) emissions, since $CO_2$ accounts for over 99% of the greenhouse gas emissions from diesel-fueled transportation sources. The analysis concludes that the revisions to the regulation will result in a 0.012% increase in $CO_2$ emissions.

The analysis of $CO_2$ emissions was done by examining the increase in $CO_2$ emissions due to the production of the lower sulfur fuel. Because the hydrotreating to reduce sulfur alters the hydrogen/carbon ratio of the diesel fuel, there is a decrease in the $CO_2$ emissions, per unit of energy, from the combustion of the resulting fuel. The balance between these two processes is the net increase given above.

The calculations were not reviewed in detail. One item of concern is the natural gas composition used in the analysis: $CH_4$, $C_2H_6$, and $CO_2$ with molar concentrations of 77.5%, 16.0% and 6.5%, respectively. This natural gas composition is not typical of natural gases in California. In addition, the heat of combustion of 18,300 $Btu/lb_m$ used for this natural gas composition does not appear to be correct.

The construction of new facilities to produce the 15 ppmw diesel fuel may cause environmental impacts. The report notes that such construction may be exempted from the need to obtain offsets, resulting in a permanent increases in emissions from stationary sources. Because of a lack of specific information in responses to the surveys sent to refiners, there is no quantitative discussion of these emission increases. On a regional basis, these increases, if any, should be less than the emission reductions from diesel engines that can be accomplished because of the use of the 15 ppmw diesel fuel. However, the potential increases in refinery emissions may be concentrated in local areas, raising concerns about ARB's environmental justice policies.

## Summary

This review has considered the technical feasibility of the proposed changes to the regulations.  Other items covered in the staff report, including the need for emission reductions, the health benefits of emission reductions, and impacts of the regulations on the California economy have not been reviewed here.

# EFFECT OF CURRENT REGULATIONS

Appendix D of the staff report reviewed here contains a March 2003 draft report titled "Staff Review of the Emission Benefits of California's Diesel Fuel Program."[*] The report concludes that the "predicted emission reductions associated with California diesel fuel averaged about 26 percent and six percent, respectively for PM and NOx." The report also concluded that reductions in sulfur compounds were "estimated to be at least 95 percent." This part of the review examines the basis for these conclusions.

## Background

The predicted emission reductions are based on an analysis of several studies that have been made on the effects of diesel fuel properties on emissions. Table 6 of Appendix D lists the 35 studies considered in the staff estimate of benefits, showing that these studies used 300 different fuels with 73 different engines or engine configurations. Over 50 of these engines had model years between 1991 and 1996. Most of these studies were also considered in the diesel fuel analysis conducted by EPA.[4,5]

The formation of sulfur dioxide and sulfates by the combustion of the fuel sulfur is straightforward. Reductions in diesel sulfur will produce proportionate reductions in sulfur oxides in the exhaust. The influence of individual diesel fuel properties on other emissions is less clear. These effects come from the ways in which fuel properties influence different parts of the diesel combustion process: the fuel injection, the initial premixed burning, and the final diffusion burning phase. In theory, individual diesel fuel properties are expected to have the following effects on the combustion process.[11]

- Higher ***cetane numbers*** reduce the ignition delay and the amount of time spent in the premixed burning phase. This reduces temperatures, which should reduce NOx emissions. Excessively high cetane numbers can increase PM.
- Fuel ***density*** and fuel ***viscosity*** influence the injection and mixing process. Reduced density is usually correlated with lower emissions.
- ***Aromatic content*** is expected to increase particulate matter whose atomic structure consists of aromatic rings. In addition, aromatic components, with their lower hydrogen to carbon ratio, produce higher temperatures for the same air/fuel equivalence ratios. Aromatic content is measured in terms of total aromatics or subdivided into ***monocyclic and polycyclic aromatics***.
- ***Distillation temperatures*** of the fuel can affect the evaporation and combustion of the fuel spray. (The temperatures at which 10%, 50% and 90% of the fuel evaporate are designated T10, T50, and T90.)
- Fuel ***sulfur*** can react to form particulate sulfate matter.

[*] In this section of the review all page numbers and table numbers without a specific document reference refer to the March 2003 "Staff Review of the Emission Benefits of California's Diesel Fuel Program" contained in Appendix D of the June 6 staff report which is the subject of this overall review.

In the combustion of diesel fuel, all these properties interact to provide the final emissions level in a given engine. The interrelationship among properties of diesel fuel can be shown by consideration of the correlation among the different fuel properties. Table 2 below was developed by EPA to show this correlation for the fuels in its database.[6] In these standardized correlation coefficients, a value of ±1 indicates a prefect correlation and a value of zero shows no correlation. The data in Table 2 show that the aromatic content of the fuels in the database is strongly correlated with the specific gravity and with natural cetane. Because of these correlations, it is not possible to unambiguously assign a particular emissions effect to a particular fuel property.

**Table 2 – Correlation of Fuel Properties in the EPA Database[6]**

| | Natural cetane | Additive cetane | Sulfur | Aromatics | T10 | T50 | T90 | Specific gravity |
|---|---|---|---|---|---|---|---|---|
| Natural cetane | 1 | -0.35 | -0.04 | -0.57 | 0.16 | 0.26 | 0.32 | -0.61 |
| Additive cetane | -0.35 | 1 | -0.17 | 0.20 | -0.08 | -0.07 | -0.10 | 0.25 |
| Sulfur | -0.04 | -0.17 | 1 | 0.30 | 0.01 | 0.11 | 0.10 | 0.21 |
| Aromatics | -0.57 | 0.20 | 0.30 | 1 | 0.13 | 0.30 | 0.23 | 0.75 |
| T10 | 0.16 | -0.08 | 0.01 | 0.13 | 1 | 0.69 | 0.30 | 0.30 |
| T50 | 0.26 | -0.07 | 0.10 | 0.30 | 0.69 | 1 | 0.70 | 0.41 |
| T90 | 0.32 | -0.10 | 0.10 | 0.23 | 0.30 | 0.70 | 1 | 0.23 |
| Specific gravity | -0.61 | 0.25 | 0.20 | 0.75 | 0.30 | 0.41 | 0.23 | 1 |

The correlation among fuel properties can lead to different conclusions regarding the fuel property that has the most significant effect on emissions. The staff report of emission benefits in Appendix D has an appendix that gives a brief summary of each study considered. Here are three extracts from those summaries deliberately chosen to show the divergence in the conclusions of individual studies: For the EPEFE study, the summary states, in part, that "[f]uel density was the most influential property to reduce NOx." The summary for SAE 932685 starts with the statement that "[i]ncreasing cetane number reduced NOx emissions whereas total aromatics content had no influence on NOx emissions." The summary for SAE 932800 says that "[t]he results of this study clearly show that aromatic content is the dominant fuel property that can be used to reduce emissions."

The collection of studies on the effects of diesel fuel properties on emissions raises an important question. How representative are these studies of actual in-use engines and fuels? Often special diesel fuel blends are used in these studies to minimize the correlation effects noted in Table 2. In addition, there are only limited data on (prototype) engines designed to operate with low NOx levels required by the 2004 standards. The further reductions required by the 2007 standards will be met by aftertreatment devices and their combustion behavior should be similar to those of 2004 engines. Thus, the effects of fuel properties on emissions should be similar for engines meeting either the 2004 or 2007 standards.

## Reductions in sulfur compounds

The report does not explicitly show the calculation of the sulfur-oxide emission benefits. The estimated reduction of at least 95% is apparently based on data in Table 3, which shows that the sulfur content of diesel fuel (statewide average, except for the South Coast Air Basin and Ventura County) was 2800 ppmw before the current regulations and averaged 133 ppmw between 1995 and 2000 (after the regulations were implemented). This reduction from 2800 to 130 ppmw corresponds to a 95.4% reduction in fuel sulfur, which should translate to a similar reduction in sulfur compounds in the exhaust. This is apparently the basis for the conclusion that sulfur compound reductions are estimated to be at least 95%.

The calculation described above includes both the 1988 rulemaking, which required sulfur reductions statewide, and an earlier reduction, which required diesel sulfur reductions in the South Coast Air Basin and Ventura County. If the benefits of only the 1988 rulemaking are desired, it is necessary to find the fraction of fuel sales in the South Coast Air Basin and Ventura County, where the fuel sulfur limit was 500 ppmw, effective January 1, 1985. If the fraction of fuel sold in these areas is denoted as f and the measured average sulfur concentration in the diesel fuel sold in that area prior to the implementation of the 1998 regulation is designated as $S_0$, the reductions attributable to the 1988 rule would be computed as follows.

$$\frac{(1-f)2800 + fS_0 - 133}{(1-f)2800 + fS_0}$$

This percent reduction will still be high. A guess that f = 40% and $S_0$ = 500 ppmw gives a percent reduction of 93%.

A third approach to evaluating the sulfur benefits of the rule is to compare the value of 330 ppmw for the average fuel sulfur (outside of California and Alaska) shown in Table 3, with the 130 ppmw value for California. This gives a reduction of 61% in sulfur when California diesel fuel is compared to current federal diesel fuel. All three approaches listed above are valid measures of the effect of the rule, provided that the basis for the comparison is made clear.

## Analysis of reductions in NOx and PM

For NOx and PM, the overall approach is clear. The ARB staff reviewed previous studies that measured the effect of diesel fuel properties on emissions. Table 6 lists these studies, which used 300 different fuels and 73 different engines or engine configurations.[*] ARB staff developed statistical relationships to represent these data. They then applied these relationships to two sets of fuel properties: (1) the properties of diesel fuel in California before the implementation of the current regulations, and (2)

[*] These numbers are different from the numbers for test programs, engines, and fuels cited in the first paragraph on page 8 of Appendix D.

average fuel properties after regulation. The estimated benefits of the regulation are the differences in emissions predicted by the statistical relationships for these two cases.

Although the overall approach is clear, the details of the calculations used to determine the PM and NOx benefits are limited. There are two separate calculations of the NOx benefits, which are presented in Table 7 and Table 9. Table 7 also presents estimates of the PM reductions, which are not contained in Table 9. Table 7 is described as "a 'mixed-modeling' statistical analysis of the test programs" reviewed by the staff. Table 9 is described as an analysis of the "U. S. EPA Diesel Fuel Effects database" with regression coefficients estimated using an "approach similar to the one used in the [Heavy Duty Engine Working Group] HDEWG study."

One of the differences between these two tables is the choice of variables used in the regression equation. For Table 7, almost all the regression equations use cetane number, sulfur, aromatics, distillation temperatures, and specific gravity as the regression variables.[*] The regression variables in Table 9 are cetane number, total aromatics, and specific gravity. There were also differences in the studies used in the two tables.[†]

Presumably, the results of the "'mixed-modeling' statistical analysis" used for Table 7 was one in which the fuel effects were treated as fixed effects and the effects of different engines were treated as random effects. This approach is commonly used in the analysis of fuel effects to account for differences in engines (which can often have a larger effect than differences in fuels). In addition, treating the engine as a random effect allows one to estimate the variance caused by different engines in the engine population from which the engines used in the study are taken.

The results in Table 9 are presented in terms of standardized regression coefficients. According to the description of the results in this table, ARB staff used "the log of the data" and a modeling "approach similar to the one used in the HDEWG study." The HDEWG statistical analysis did not use log transformations. That study did various analyses to check for outliers, determine the significance of individual variables, and to see how well the results of the regression satisfied the assumptions for regression analysis.[12] There is no indication that similar data checks were done in the Table 9 analysis.

Because very little information is given about the details of the regression analyses that give the results in Tables 7 and 9, one can ask several questions about the way these were done. For example, were log transformations used for the emissions or fuel property variables? Were the fuel properties used directly in the equations or were they centered or normalized before the analysis? Were all three distillation temperatures used in the analyses? No values are given for the distillation temperatures in the before

[*] For one study (SAE 961974) the only variable was sulfur; for another study (SAE 1999-01-1117) distillation temperatures were not used in the regression.

[†] The following studies in Table 7 were not included in Table 9: SAE 1999-01-1117, SAE 1999-01-3606, SAE 790490. SAE 852078, and SAE 881173.

and after fuel properties; what values were used in the analysis? What was the significance level of the fuel-property regression coefficients in the various studies? What was done in the fuel property data that were not available for one study or for one or more fuels in a study? How were the data for repeat experiments on individual fuels and engines grouped for the final regression results on individual studies? How were the overall reductions determined from the data on individual studies? Were the data from the different studies weighted to account for the distribution of engines in the on-road fleet?

Because of all these questions, the ARB staff should post the data that they used, with a longer description of the exact methods, on the ARB web site so that they are publicly available for individuals to review and confirm the analyses.

A simplified analysis of two studies, ACEA and SAE 1999-01-1478, was done as part of this review, using the simple linear regression functions of Excel. The data were taken from the EPA database.[13] Each study used only one engine and the regressions used only cetane number, specific gravity and aromatics content as the variables in the regression equation. These were the same values used by ARB staff in Table 9. The percent reductions in PM and NOx using these simplified analyses were determined by using the pre-1993 and 1995-2000 data in Table 3 of Appendix D as the before and after property data. Details of these calculations are contained in the appendix to this review and the results are shown in Table 3.

**Table 3 – Comparison of Percent Reductions Computed Here with Values in Tables 7 and 9 of Staff Report Appendix D**

| Study | Engine Model Year | NOx Reductions | | | PM Reductions | |
|---|---|---|---|---|---|---|
| | | Computed | Table 7 | Table 9 | Computed | Table 7 |
| ACEA | 1991 | 3.1% | 3.3% | 5.0% | 11.1% | 43.4% |
| SAE 1999-01-1478 | 1993 | 5.5% | 5.1% | 5.4% | 3.5% | 3.9% |

**Note:** The engines used in both studies were turbocharged, direct-injection Detroit Diesel engines with a displacement of 11.1 liters and a rated output of 330 HP.

The agreement between the calculations here and those in Appendix D are reasonable for the estimated NOx reductions and the estimated PM reductions from the SAE 1999-01-1478 study. However, the estimated PM reductions from the ACEA study are not close to those shown in Table 7. The reason for this is not clear. ARB staff may have used data from the original study, which are different from those in the EPA database. Also, Table 7 states that distillation temperatures and sulfur were used in addition to cetane, aromatics and specific gravity as regression variables. This was not done here because the sulfur level and distillation temperature data were not available for all the data in the ACEA study.

### Fuel effects in engines equipped with exhaust gas recirculation (EGR)

One of the issues not discussed in detail in Appendix D is the possible difference in the emission reductions of clean diesel fuel on engines that are equipped with EGR. In its consideration of the Texas low emission diesel (LED) fuel program, EPA allowed a 6.2% reduction in NOx from engines without EGR and 4.8% for engines with EGR.[14] These values are apparently based on the regression equations EPA developed and applied to its data for baseline national diesel fuel and California diesel fuel.[5] (The coefficients in the EPA regression equation are shown in Table 8 of Appendix D.)

All the data used to develop the regression equations with EGR were obtained in two studies on a single engine, a Caterpillar 3176.[*] The original engine was designed with emission controls to meet 1994 standards and was "considered state of the art for the 1994-1997 year models."[15] It was modified to include EGR to determine the fuel effects on a prototype engine for the 2004 emission standards. Both studies obtained data over the steady-state, eight-mode AVL cycle which has been shown to correlate with the transient test procedure for gaseous emissions, but not for particulate emissions.

In the HDEWG II study, fuel properties were controlled so that the effect of individual fuel properties could be determined. The following observations were made about the cetane response of the engine used in the study:[15]

- The overall conclusion was that the engine had a "very low sensitivity to cetane number . . . [that] differs from the results of similar experiments in engines that are not equipped with EGR."
- Table 5 of the paper showed that the regression coefficient for NOx with cetane had a small positive value whose p-value (level of significance) was 0.024.
- Figure 2 of the paper showed that an increase in cetane number from 42 to 52 would *increase* NOx by 1.3%.

The paper reported data with and without EGR, but did not explicitly compare the effects of cetane on NOx, with and without EGR. Table 4, below, is taken from Table 8 of the HDEWG statistical results paper.[12] The NOx results in this table are the averages of the entries for two fuels with the same cetane number in the original paper. The fuels that have an N in their designation are natural cetane fuels that do not have any additized cetane. *E.g.*, fuels 16 and 16N are both reported as having a "target" cetane level of 52. The paper also analyzed the emission results from fuels with the same cetane number where one fuel had cetane improving additives and the other did not. This analysis showed that the effect of a natural cetane number could not be statistically distinguished from the effects of fuels where the same cetane number was produced by an additive to improve cetane. Thus, it is reasonable to compare fuels in this study with the same cetane numbers, regardless of how they are obtained.

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[*] The study/engine combinations for this engine are noted in Table 9 of Appendix D as the HDEWG II study with the HDEWG EGR engine and the SAE 2000-01-2880 study with the 04 SWRI/CAT 10.3 engine.

**Table 4 – HDEWG Data for Cetane NOx Effect With and Without EGR[8]**

| Fuels | Cetane | NOx data with EGR | | | NOx without EGR | | |
|---|---|---|---|---|---|---|---|
| | | g/bhp-hr | Percent change | | g/bhp-hr | Percent change | |
| 7N+14N | 42 | 2.368 | Per step | Initial to final | 3.740 | Per step | Initial to final |
| 8+8N | 47 | 2.415 | 2.0% | | 3.803 | 1.7% | |
| 16+16N | 52 | 2.346 | -2.9% | -0.9% | 3.684 | -3.1% | -1.5% |

The results of Table 4 show that the effect of cetane on NOx is similar with or without EGR, for the engine used in the study. In both cases, there is an increase of about 2% as the cetane number is increased from 42 to 47 and a decrease of about 3% as the cetane number is increased from 47 to 52. The overall effect of increasing the cetane number from 42 to 52 is a NOx decrease of 0.9% with EGR and a NOx decrease of 1.5% without EGR.

Table 4 shows that the effects of cetane on NOx for this engine are similar with and without EGR. Although the engine has a low sensitivity to cetane, it is likely that this effect is not due to EGR. Instead, it is due to some other differences between this engine and engines tested previously. The most likely explanation is that fuel injection controls on newer diesel engines have changed the combustion process to significantly reduce the amount of premixed combustion. The discussion of Figures 9 to 12 of the HDEWG test result paper states that "there is very little premixed burning…."[15] Since the premixed burning phase of diesel combustion is the one that is affected by changes in cetane number, an engine that is designed to nearly eliminate this premixed-burning phase should have a low sensitivity to cetane. This hypothesis was also suggested in the other study that used this EGR engine.[16]

EPA's cetane report[6] analyzed the sensitivity of NOx reduction to change in cetane over model years from 1991 to 1998. The Agency wanted to determine whether this sensitivity decreased over time, indicating that newer engines might have less sensitivity to cetane because of their design. EPA found that there was a decrease in this sensitivity, but it was not statistically significant.

The ARB staff analysis of this engine in Appendix D, Table 9, shows that California diesel fuel should achieve NOx reductions of 5.6% from the data in the HDEWG II study and 7% for the data in the SAE 2000-01-2890 study. These data are similar to the results from other studies and no overall percent reduction was computed in Table 9. The EPA analysis, based on data for this engine and a comparison of national baseline fuel to California diesel determined that the NOx reduction was 4.8%.

One study not considered in the staff report or EPA database used an advanced light-duty engine developed as part of the government-industry partnership for a new generation of vehicles (PNGV) program.[11] This engine had both electronic injection and EGR. This study looked only at a few operating points, rather than a duty cycle, to improve understanding of emission reductions by fuel properties. The fuels used included California diesel and three other fuels that were designed to be cleaner than California diesel. The study concluded that additional reductions in NOx and PM were possible, in advanced engines for light-duty vehicles, by using cleaner diesel fuels.

Because of the lack of data on prototype engines designed to meet future emission standards, there are no firm conclusions about such engines. However, the data on a single heavy-duty engine indicate that future heavy-duty engines, with advanced fuel injection systems that reduce premixed burning or EGR, may provide less NOx emission reduction from clean diesel fuel than engines in the current fleet.

### Conclusions regarding NOx and PM benefits

Despite all the difficulties with the technical analysis of the effect of fuel properties on exhaust emissions, all studies on this subject show that changes in diesel fuel properties can reduce emissions. Although different studies identify different variables as important and the quantitative results from such studies have a large variability, there is a general conclusion that reductions in aromatics and density and increases in cetane number can reduce emissions of NOx and particulate matter.

The differences in NOx reduction for the same studies that are shown in both Table 7 and Table 9 of Appendix D illustrate the problems associated with a quantitative determination of benefits. However, studies of diesel fuel impact on emissions, taken as a whole, show that appropriate fuel blends can reduce emissions, even if the exact relationship between fuel properties and emission reduction is not quantitatively known.

Limited data on one heavy-duty engine, developed as a prototype to meet the 2004 standards, indicate that future engines may have less NOx reduction benefit than older engines.

# CONCLUSIONS

The proposed regulation changes center on the reduction of sulfur in diesel fuel. The main reason for this regulation is to allow the use of advanced emission control technologies such as NOx adsorbers and catalytic particulate traps on diesel engines. This regulation is consistent with current EPA regulations for 15 ppmw sulfur fuel in highway vehicles and proposed EPA regulations for such fuel in offroad engines. The major conclusions about the proposed revisions are summarized below.

- The proposed 15 ppmw sulfur diesel fuel is technologically feasible and is necessary to allow the use of advanced emission control technologies on diesel engines.
- The cost of the modifications will be a few cents per gallon of diesel fuel.
- The requirement for a lubricity standard is consistent with the need to provide good lubricating properties in low-sulfur diesel fuels. The choice to have such a standard in the regulations, as opposed to a voluntary program, is a policy question, not a technical question.
- The establishment of a specific set of fuel properties to define alternative fuel formulations without engine testing should provide similar emission reductions without the need for costly engine tests.
- The revised acceptance criterion for alternative fuel formulations should provide greater assurance that these formulations have lower emissions than the candidate fuels that comply with the 10%v aromatics standard.

This review also examined the draft staff report on the evaluation of the benefits from the current regulations contained in Appendix D of the staff report. This review drew the following major conclusions.

- The reduction in exhaust sulfur oxides is directly proportional to the concentration of sulfur in the diesel fuel. The percent reduction depends on the baseline used for the calculations.
- Reductions of other compounds, in particular NOx and PM, are difficult to evaluate because of conflicting results of studies to measure the effects of fuel properties on these emissions. The differences in these results are often due to the strong correlation among diesel fuel properties, which makes it difficult to unambiguously assign emission reduction values to individual fuel properties.
- Despite the previous conclusion, published studies of the effect of diesel fuel properties on NOx and PM emissions generally show that reductions in density and aromatics and increases in cetane number will reduce emissions of NOx and PM. Other diesel fuel properties have been used in some studies to correlate emission reductions.
- Limited test results indicate that the effect of fuel properties on NOx reductions may be less in future engines.

# REFERENCES

[1] California Air Resources Board, "Proposed Amendments to the California Diesel Fuel Regulations Staff Report: Initial Statement of Reasons," June 6, 2003.

[2] *Federal Register* **66**, 5002–5193, January 18, 2001.

[3] *Federal Register* **68**, 28328–28603, May 23, 2003.

[4] Robert L. Mason and Janet P. Buckingham, "A Diesel Fuel Impact Model Data Analysis Plan Review, Draft Final Report, Work Assignment 2-7," EPA Contract 68-C-98-169, Southwest Research Institute, July 2001.

[5] U. S. Environmental Protection Agency, "Strategies and Issues in Correlating Diesel Fuel Properties with Emissions," Staff Discussion Document EPA420-P-01-001, July 2001.

[6] U. S. Environmental Protection Agency, "The Effect of Cetane Number Increase Due to Additives on NOx Emissions from Heavy-Duty Highway Engines," Final Technical Report EPA420-R-03-002, Office of Transportation and Air Quality, February, 2003.

[7] U. S. Environmental Protection Agency, "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements," USEPA Office of Air and Radiation, Report EPA420-R-00-026, December 2000.

[8] U. S. Environmental Protection Agency, "Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements: Response to Comments," USEPA Office of Transportation and Air Quality, Report EPA420-R-00-027, December 2000.

[9] U. S. Environmental Protection Agency, "Highway Diesel Progress Review," USEPA Office of Transportation and Air Quality, Report EPA420-R-02-016, June 2002.

[10] Clean Diesel Independent Review Subcommittee, "Final Report Meeting Technology Challenges for the 2007 Heavy-Duty Highway Diesel Rule," presented to the Clean Air Act Advisory Committee, Washington, D. C., October 30, 2002.

[11] Timothy P. Gardner, Scott S. Low, and Thomas E. Kenny, "Evaluation of Some Alternative Diesel Fuels for Low Emissions and Improved Fuel Economy," SAE Paper 2001-010149, presented at SAE World Congress, Detroit, Michigan, March 5-8, 2001.

[12] Robert L. Mason *et al.*, "EPA HDEWG Program – Statistical Analysis," SAE Paper 2000-01-1859, presented at International Spring Fuel and Lubricants Meeting, Paris, France, June 19-22, 2000.

[13] This database is in the Excel file hdd-db7.xls, available at the EPA diesel-analysis web site, http://www.epa.gov/otaq/models/analysis.htm. This is version seven of the database, dated June 12, 2001, which contains all the repeat data and cycle data that EPA rejected in previous analyses.

[14] Memorandum from Robert Larson, Acting Director, Transportation and Regional Programs to Karl Edlund, EPA Region VI, "Texas Low Emission Diesel (LED) Fuel Benefits," September 27, 2001.

[15] Andrew C. Matheaus, *et al.*, "EPA HDEWG Program – Engine Tests Results," SAE Paper 2000-01-1858, presented at International Spring Fuel and Lubricants Meeting, Paris, France, June 19-22, 2000.

[16] Ken Mitchell, “Effects of Fuel Properties and Source on Emissions from Five Different Heavy Duty Diesel Engines,” Society of Automotive Engineers paper 2000-01-2890, presented at International Fall Fuels and Lubricants Meeting and Exposition, Baltimore, Maryland, October 16-19, 2000.

# APPENDIX

The two spreadsheets shown in this appendix use a simple regression analysis of the data for two studies in the EPA database, using the linest function of Excel. Regression coefficients are computed for NOx and PM emission rates (in g/bhp-hr) using cetane number, aromatics content and specific gravity as the regression variables. Once the regression coefficients are determined, the reduction in NOx and PM emissions is computed by applying these coefficients to two different sets of diesel fuel properties. These fuel properties are the same ones used in the ARB staff analysis.

# Regression Analysis of ACEA Data

| Fuel | NOx | PM | Cetane | Aromatics | Sp grav | Repeats |
|---|---|---|---|---|---|---|
| EPD11 | 4.2283 | 0.1543 | 57.1 | 16.94 | 0.827 | 3 |
| EPD6 | 4.259 | 0.1797 | 50.2 | 27.34 | 0.8555 | 3 |
| EPD9 | 4.2568 | 0.1847 | 59.1 | 28.61 | 0.8554 | 3 |
| RFCAL | 4.1349 | 0.1673 | 49.9 | 12.913 | 0.8445 | 9 |
| SC1 | 4.0647 | 0.1349 | 57.9 | 2.62 | 0.8144 | 3 |

Data taken from EPA data base; each repeat has identical data; this procedure was followed by EPA when original reference gave the number of repeat tests, but only average results instead of results for each test.

NOx regression

| | Sp grav | Aromatics | Cetane | Intercept |
|---|---|---|---|---|
| Coefficients | -3.42779 | 0.01246884 | -0.003628 | 7.045863 |
| Coefficient Std. Errors | 0.423619 | 0.00063059 | 0.0008789 | 0.3853 |
| R2 / Std err | 0.983932 | 0.00975491 | #N/A | #N/A |
| F/ df | 347.0025 | 17 | #N/A | #N/A |
| sums of squares | 0.09906 | 0.00161769 | #N/A | #N/A |
| t value | -8.09169 | 19.7733748 | -4.127825 | 18.28671 |
| p(coeff = 0) | 3.12E-07 | 3.6051E-13 | 0.0007031 | 1.29E-12 |

Calculate percent reduction from California Diesel

| Property | Coefficient | Pre-reg | Post-reg |
|---|---|---|---|
| Intercept | 7.0458633 | 1 | 1 |
| Sp grav | -3.43E+00 | 0.856 | 0.837 |
| Cetane | -3.63E-03 | 45 | 52 |
| Aromatics | 1.25E-02 | 36 | 22 |
| Emissions (g/bhp-hr) | | 4.40 | 4.26 |
| **Percent NOx reduction** | | | **-3.1%** |

Particulate Regression

| | Sp grav | Aromatics | Cetane | Intercept |
|---|---|---|---|---|
| Coefficients | 1.005851 | 0.00024651 | 0.0003247 | -0.70205 |
| Coefficient Std. Errors | 0.057788 | 8.6022E-05 | 0.0001199 | 0.052561 |
| R2 / Std err | 0.993883 | 0.00133072 | #N/A | #N/A |
| F/ df | 920.7458 | 17 | #N/A | #N/A |
| sums of squares | 0.004891 | 3.0104E-05 | #N/A | #N/A |
| t value | 17.40579 | 2.86570535 | 2.7084849 | -13.3569 |
| p(coeff = 0) | 2.86E-12 | 0.01071272 | 0.0149085 | 1.92E-10 |

Calculate percent reduction from California Diesel

| Property | Coefficient | Pre-reg | Post-reg |
|---|---|---|---|
| Intercept | -0.70204983 | 1 | 1 |
| Sp grav | 1.01E+00 | 0.856 | 0.837 |
| Cetane | 3.25E-04 | 45 | 52 |
| Aromatics | 2.47E-04 | 36 | 22 |
| Emissions (g/bhp-hr) | | 0.18 | 0.16 |
| **Percent PM reduction** | | | **-11.1%** |

Regression analysis used linest function of Excel.
Before and after properties taken from Appendix D, Table 3, of June 6, 2003 ARB staff report on proposed new revisions to California Diesel Fuel regulations.
All "repeat" data (21 points total) used in the regression analysis.

# Regression Results for 1999-01-1478 Study

| Fuel | NOx | PM | Cetane | Aromatics | Sp Grav | Repeats |
|---|---|---|---|---|---|---|
| FUEL1 | 5.139 | 0.1421 | 39.7 | 43.4 | 0.86 | 16 |
| FUEL1A | 5.08 | 0.1369 | 42.1 | 43.4 | 0.86 | 4 |
| FUEL1B | 5.047 | 0.1349 | 43.2 | 43.4 | 0.86 | 4 |
| FUEL1C | 4.973 | 0.134 | 45.8 | 43.4 | 0.86 | 5 |
| FUEL1D | 4.92 | 0.1309 | 47.9 | 43.4 | 0.86 | 5 |
| FUEL1E | 4.918 | 0.1316 | 51.1 | 43.4 | 0.86 | 4 |
| FUEL1F | 5.096 | 0.1378 | 41.6 | 43.4 | 0.86 | 6 |
| FUEL1G | 5.047 | 0.138 | 42.5 | 43.4 | 0.86 | 6 |
| FUEL1H | 5.018 | 0.1341 | 45.7 | 43.4 | 0.86 | 6 |
| FUEL1I | 4.946 | 0.135 | 47.9 | 43.4 | 0.86 | 4 |
| FUEL1J | 4.883 | 0.1301 | 51.1 | 43.4 | 0.86 | 4 |
| FUEL2 | 4.813 | 0.1351 | 46.3 | 29.2 | 0.849 | 17 |
| FUEL2A | 4.757 | 0.135 | 48.9 | 29.2 | 0.849 | 5 |
| FUEL2B | 4.733 | 0.1314 | 51.6 | 29.2 | 0.849 | 4 |
| FUEL2C | 4.738 | 0.1274 | 54.6 | 29.2 | 0.849 | 4 |
| FUEL2D | 4.713 | 0.126 | 59.1 | 29.2 | 0.849 | 4 |
| FUEL2E | 4.722 | 0.1255 | 60.5 | 29.2 | 0.849 | 4 |
| FUEL2F | 4.762 | 0.134 | 48.3 | 29.2 | 0.849 | 6 |
| FUEL2G | 4.783 | 0.1309 | 51.1 | 29.2 | 0.849 | 6 |
| FUEL2H | 4.752 | 0.128 | 54.9 | 29.2 | 0.849 | 4 |
| FUEL2I | 4.718 | 0.1297 | 58.4 | 29.2 | 0.849 | 4 |
| FUEL2J | 4.671 | 0.1263 | 61.2 | 29.2 | 0.849 | 4 |

Data taken from EPA data base; each repeat has identical data; this procedure was followed by EPA when original reference gave the number of repeat tests, but only average results instead of results for each test.

NOx Regression

| | Sp grav | Aromatics | Cetane | Intercept |
|---|---|---|---|---|
| Coefficients | 1.495378 | 0.011256 | -0.012345 | 3.803826295 |
| Coefficient Std. Errors | 0 | 0 | 0.000727 | 0 |
| R2 / Std err | 0.941593 | 0.037601 | #N/A | #N/A |
| F/ df | 655.5996 | 122 | #N/A | #N/A |
| sums of squares | 2.780799 | 0.172492 | #N/A | #N/A |

Calculate percent NOx reduction from California Diesel

| Property | Coefficient | Pre-reg | Post-reg |
|---|---|---|---|
| Intercept | 3.803826 | 1 | 1 |
| Sp grav | 1.50E+00 | 0.856 | 0.837 |
| Cetane | -1.23E-02 | 45 | 52 |
| Aromatics | 1.13E-02 | 36.00 | 22 |
| Emissions (g/bhp-hr) | | 4.93 | 4.66 |
| **Percent NOx reduction** | | | **-5.5%** |

Regression analysis used linest function of Excel.

Before and after properties taken from Appendix D, Table 3, of June 6, 2003 ARB staff report on proposed new revisions to California Diesel Fuel regulations.

All repeat data (126 data points total) used in regression calcualtions.

PM Regression

| Sp grav | Aromatics | Cetane | Intercept |
|---|---|---|---|
| 0.04688 | -0.000102 | -0.000766 | 0.134359472 |
| 0 | 0 | 2.91E-05 | 0 |
| 0.897252 | 0.001505 | #N/A | #N/A |
| 355.1238 | 122 | #N/A | #N/A |
| 0.002412 | 0.000276 | #N/A | #N/A |

Calculate percent PM reduction from California Diesel

| Property | Coefficient | Pre-reg | Post-reg |
|---|---|---|---|
| Intercept | 0.134359 | 1 | 1 |
| Sp grav | 4.69E-02 | 0.856 | 0.837 |
| Cetane | -7.66E-04 | 45 | 52 |
| Aromatics | -1.02E-04 | 36.00 | 22 |
| Emissions (g/bhp-hr) | | 0.136 | 0.131 |
| **Percent PM reduction** | | | **-3.5%** |